Disassembly 4.0: A Review on Using Robotics in Disassembly Tasks as a Way of Automation

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To successfully implement circular economy processes into present value chains, economic feasibility of disassembly processes is essential. Current developments in science and technology, such as artificial intelligence and Internet of Things, foster steep progression in the field of robotics. In this review, the current research on robotics in disassembly is investigated by a systematic literature review. The results were clustered in a framework system distinguishing between applied and basic research on the two main streams of disassembly automation research, namely, predefined processes and adaptable, flexible automation.

Keywords: Automation technologies, Circular economy, Disassembly, Industry 4.0, Robotics

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1 Introduction

1.1 Background and Motivation

Several risk factors are currently challenging society as a whole, such as climate change, shifting of economic output, and the strongly increasing political relevance of global raw material reserves. Hence, public opinion concerning the importance of recycling is changing from an opportunistic position to a strategic, yet elementary, component of economic and scientific considerations in all major related fields. Whereas many research contributions in the broad field of robotics aim at problems concerning assembly tasks in industrial production processes, disassembly has not been in the focus of mainstream robotics research so far, apart from specific sequence planning research, such as [1]. Therefore, a systematic literature review (SLR) on the state-of-the-art at the point of intersection between robotic technologies and research fields within the circular economy (CE) seems to be necessary.

Following the four steps of the recycling chain [2], from collection and sorting via preparation and disassembly to mechanical and chemical processing and, finally, to the recovery of raw materials, disassembly processes usually include the largest number of employees and the highest complexity in end-of-life (EOL) treatments. This depends mostly on the product complexity itself and design issues, making disassembly more complex than general assembly tasks, be it for recycling or second life and remanufacturing purposes [3]. The project "Recycling 4.0", funded by the European Regional Development Fund, investigates the integration of digitalization technologies into CE to improve the overall process by the integration and management of information flows. In this research project, the general disassembly workflow was assessed in collaboration with the project's industry partners. As displayed in Fig. 1, the process consists of five steps, covering the entire handling of the EOL product from collection to further processing in terms of recycling or reuse and remanufacturing of components.

The reason for pursuing the automation of this process is mostly its inefficiency and, therefore, economic infeasibility for many potential disassembly products at the moment. So far, various attempts have been made to automate disassembly for highly complex products, such as cars and mechanical components, but none of them has been implemented on an industrial scale yet. With the concept of a thoroughly circular economy in mind, the implementation of a more

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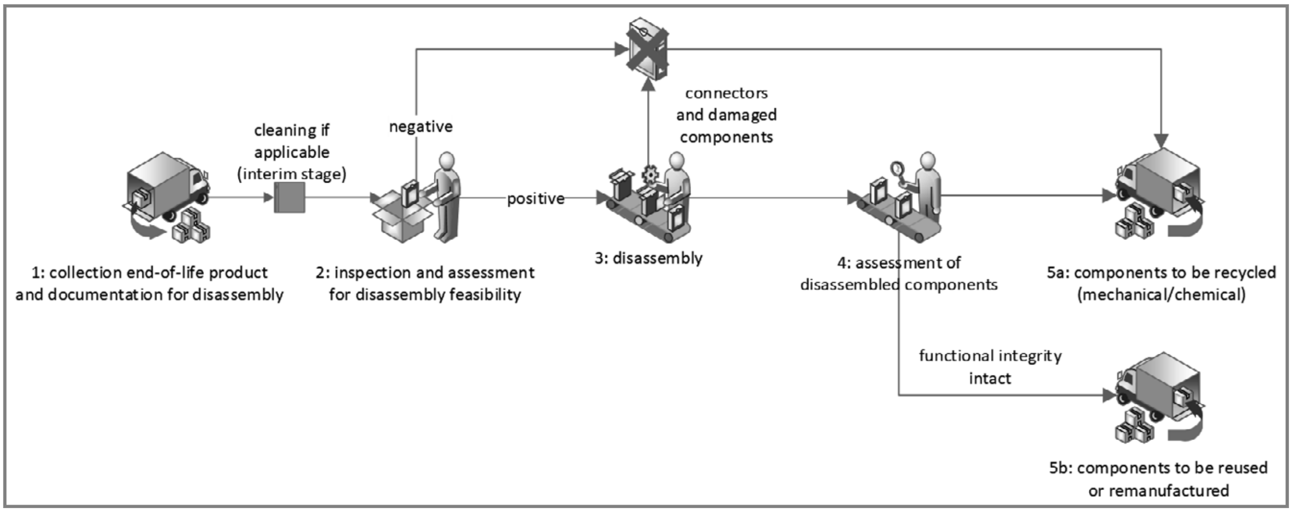

Figure 1. General disassembly process chain.

advanced disassembly is a mandatory subtask. Having many advantages of the latest developments in Industry 4.0 and especially with cooperative and collaborative robots at hand, disassembly automation might be seen as state-of-the-art in the industrial context within the next decade. This publication is intended to give a comprehensive overview of the relevant research directions and the latest developments in the field of robotics applied in disassembly contexts.

The global robotics market is growing tremendously fast. In 2017, global robot sales increased by 30 % to 381 335 units, peaking for the fifth year in a row [4]. In the future, robots will be more popular than they already are today, which is mainly because of decreasing prices and the upcoming of cooperative and collaborative designs. Sensor prices are also dropping sharply as Industry 4.0 and Internet of Things (IoT) become more common in the manufacturing industry [5] and in remanufacturing [6]. Intelligent automation is an integral part of the fourth industrial revolution, combining robots and peripheral infrastructure to cyber-physical factory systems. Adaptive grippers and the implementation of AI technologies contribute further to more flexible use cases. The World Economic Forum described robotics and automation as a positive development for the future of jobs and employment [7], leading to cooperative ways of human and machine workers complementing each other. Disassembly processes will not be able to ignore this development. It will be essential for the future success of EOL product treatment companies to adapt robotics and automation in their processes to be competitive on the market.

CE is a main idea conceptualizing material and financial circuits for a sustainable approach towards production and retroproduction systems. Kirchherr et al. [8] published an analysis of 114 different definitions of the term, showing the bold ambiguity of how it is understood by researchers of different interest groups and stating major differences depending on the group of stakeholders the authors belong to. Whereas economic and environmental benefits are in focus, social dimensions are often neglected. A key point in all research concepts of CE is the principle of 4 R (reduce, reuse, recycle, and recover) with a strong practical emphasis on recycling and sometimes extended to a broader approach of up to 10 R [9]. However, a correct use of terms in this context cannot be found universally. A clear difference between recycling and remanufacturing, e.g., lies in the fact that a remanufactured part is functionally equivalent to a new part and is virtually indistinguishable from it, while the recycled part does not necessarily have the process step of dismantling and reprocessing. Ghisellini et al. [10] emphasize the diverse theoretical background of the fields of science involved. They conclude by stating that CE is very important as a contributing factor towards an efficient and environmentally friendly transition of production and consumption procedures within a steady state-oriented economic system.

Closed-loop supply chains also play a central role in the concept of CE. Keeping materials on the highest possible economic value hierarchy level requires a sophisticated logistics concept. Employing IoT and Industry 4.0 technologies could be a major catalyst towards an integrated approach of digitized logistics [11], leading to improved product qualities and new business concepts. Cerdas et al. [12] define the concept of a circulation factory, in which they establish a closed loop flow within the boundaries of a single production and retroproduction facility. Moreover, the integration of an intelligent information flow could cut costs and use networking effects to enhance sustainability and profitability goals by the creation of intelligent value chains [5]. An advanced branch in terms of CE is waste electrical or electronic equipment (WEEE). Following a report by the World Economic Forum in support of the United Nations E-waste Coalition [13], 20 % of global WEEE is documented, collected, and recycled. From an annual generation of 44.7 million metric tons of e-waste [13], there is still a huge economic potential to be realized by applying CE concepts in the future. The leverage of an improved disassembly process across all relevant branches is therefore enormous in economic, environmental, and social dimensions.

1.2 Relevance of Topic

Following the resolution adopted by the General Assembly of the United Nations on September 25, 2015 [14], sustainable consumption and production patterns are one main aspect of the sustainable development goals as a part of the United Nations Agenda 2030. CE, and therefore disassembly processes, are necessary to fulfil those ambitions. However, automation of disassembly using robots has not yet reached broad application in industry and public waste management. There are few facilities available, e.g., Daisy and its predecessor Liam, robotic recycling and disassembly machines built by Apple Inc. [15], which cover only small numbers for recycling in relation to devices produced. Currently, there are many inhibitors regarding the disassembly process, which have to be overcome for the successful economic feasibility of concepts on an industrial scale (Tab. 1).

Numbers of publications on the topics of robotics and disassembly alone have risen steadily in the past years, e.g., the number of papers in Web of Science on the keyword "robotics" has almost quadrupled since 2008 (1993 to 7437 in 2018). Although the research directions alone expanded with a strong momentum, the research connecting the two disciplines still remains on a low level in absolute numbers. A Science Direct research on "robotics" and "disassembly" only gives 154 results for 2018, compared to 109 for 2013, which is an increase of over 40 %. This interdisciplinary research is profiting enormously from the emerging trends in robotics (e.g., cost effectiveness, IoT, AI) and the growing awareness of the importance of sustainable CE processes in a wide spread of different branches. However, no systematic approach has been made to cover the entire range of research on this topic in a scientific context. Hence, this paper aims to give an overview about the concrete research emerging from the diverse backgrounds the topic of robotics in disassembly is linked to.

1.3 Contributions of Review Papers

Based on the search engines and strings[1)] employed (see Sect. 2), no exact match of any prior review on this very topic could be found as of March 2019. The most relevant study close to linking disassembly processes to technological advances on a meta level was published by Okorie et al. [9], reviewing digital technologies applied in the context of CE. The authors based their work on the growing significance of those topics, knowing that there was no framework approach ever made to link digital technology research to the CE field. They carried out a *SLR* (n = 174) on papers published between 2000 and early 2018. Moving on from this top-level approach, Ghandi et al. [16] went more into the details of actual planning problems in assembly and disassembly (APP/DAPP). Their work presented a state-of-the-art review of the assembly and disassembly path planning while proposing new taxonomies for the categorization of problem types and solution methods. Ghandi's work is primarily method- and object-oriented, thus, the discussed literature is always considered following a content-based approach, not a systematic review process. On the other hand, the adjacent review paper by Goodall et al. [17] follows a classical review methodology by focusing on highly cited journal publications. Their approach lay in the evaluation of tools and techniques used to establish feasibility of remanufacturing processes. Iacob et al. [18] focused their research on optimization and virtual simulation methods for assembly and disassembly processes. In this context, a comparative review on such techniques was proposed in the addressed paper. Seward et al. [19] published a review paper on the use of robotics and automation in a field close to disassembly – the decommissioning of nuclear facilities. Even though this work was carried out almost 15 years ago, the

Table 1. Problems in disassembly identified in the project Recycling 4.0.

Inhibitor	Workforce	Process	Product	Information	Connectors	Logistics
Aspects	cost	flexibility	high number of variants	requirements	variety of connection technologies	cost
	qualification	high planning costs	variety of product conditions	part history	disassemblability	transparency
		low level of technology	material diversity	components	damaging risk	
		no optimization		location of valuable parts missing		

1) Limiting the search string results of "robot* AND disassembly" to reviews only on semanticscholar.org.

approach of methodically assessing the scope from the evaluation of the relevant processes can still be considered valid for present and future proposals.

1.4 Objective and Research Question

This paper investigates a holistic perspective on the research field of robotics in the context of disassembly applications. Vongbunyong et al. [20] concluded that many problems surrounding robotic automation are not yet sufficiently solved, such as sequencing, vertical range of disassembly, high number of variants, flexibility of disassembly facilities, tooling, part conditions, logistics, and information flow.

Under these circumstances, the reviewed publications will be clustered and organized in, as the authors maintain, the most relevant categories applicable to differentiate the diverse research trends. A key element in this investigation is the vertical integration in the framework of CE and recycling industry research. Most research on CE itself and also recycling and disassembly is conducted on a systems level, not taking the engineering problems of actual automation solutions into account (Fig. 2). The shopfloor level [21] is much more associated with robotics and automation research. Disassembly automation from a technological point of view has to take place on this level, as the technological peer group lies in automation and robotics research.

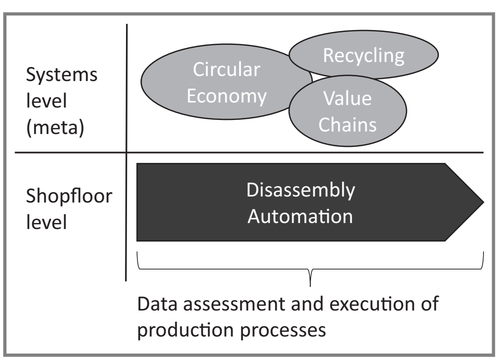

Figure 2. Disassembly automation vertical integration level of relevance in peer group context.

Separate research on robotics and automation as single topics has increased immensely over the last decade, leading to advanced and detailed results in many subfields. However, disassembly and especially automated disassembly is still a very small field of research, driven by the motivation of only a few global academic researchers and industrial practitioners. To take this into account, the following research questions can be seen as the foundation of this paper's inquiry:

- How could a research framework of robotic disassembly automation be set up following the trends and publications established with regard to the identified problems of disassembly automation in general?
- Which effects can be projected on the future development of this research field and which research gaps can be identified on the basis of the current academic canon?

The research questions originate in the idea that, on the one hand, a systematic review and structuring of the current research status could validate the pre-assessed problems and identify research momentum in specific directions and subfields; on the other hand, a review and categorization of the past research clearly shows the gaps and possibilities for new research proposals in future work. Furthermore, focusing on the integration of the fields and following a synthesis-aimed approach, many researchers would profit from the exposition of links and similarities. Accordingly, this research is an approach to merge the two fields in a single examination. Consequently, the objectives are as follows:

- Giving a comprehensive overview about robotics and disassembly integrating research by conducting an SLR on a combination of the key terms
- Identifying trends and gaps for the benefit of future research
- Structuring the research in different research directions and fields

To achieve the objectives, the review should be structured and systematic. Therefore, the paper describes the review methodology and the design of the study in Sect. 2. The process of the actual paper selection is laid out in Sect. 3, followed by a descriptive analysis in Sect. 4. The content analysis and classification are carried out in Sect. 5, being the main result of this research. Sect. 6 contains conclusions and future implications of the findings of this study.

2 Review Methodology

This research is based on the process of a systematic literature review, following the principles of the "PRISMA Statement and Checklist for Scientific Integrity" [22]. The ability of an SLR to deliver holistic and reproducible output encourages future practitioners to adapt the results as foundations for advanced research proposals. The phases of the SLR conducted here were adapted from PRISMA, Tranfield et al. [23], and Khan et al. [24] and can be seen in Fig. 3.

As the medium of research, the Semantic Scholar engine was utilized. Semantic Scholar is a project by the Allen Institute of Artificial Intelligence (AI2), working with a machine learning, natural language processing, and machine vision-based principle of explicit semantic ranking (ESR) [25]. In its ranking system, Semantic Scholar combines query terms with other document features, such as citation count and publication time in a dynamically learning architecture, focusing on the semantic intent of user queries [26]. In terms of comprehensiveness, the reasons for choosing Semantic Scholar can be illustrated using the example of the search string "robot* AND disassembly" over a period of all years available. With 74 results from Web of Science and 1927 results from Science Direct, Semantic Scholar returned

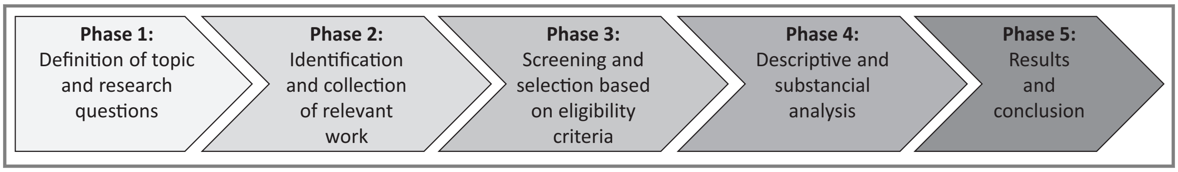

Figure 3. Phases of systematic literature review as adapted from Moher et al. [22], Tranfield et al. [23], and Khan et al. [24].

over 5000 results from more diverse backgrounds, with the results of the output in general being more relevant than those of Google Scholar [27]. For the review protocol, the limitations given in Tab. 2 were set.

Table 2. Literature review protocol.

Item	Description
Search string and operators	"robot* AND disassembly"
Time period	January 1989 – March 2019 (search performed in March 2019)
Language	English, German (on secondarily identified sources only)
Availability	articles available online as full text directly or via distributor
Publication type	peer-reviewed academic journals, conference papers, reports, books published, scientific theses available
Exclusion criteria	publications unrelated to the topic/ contrary to selection criteria

As the objectives and research questions of the study aim at an overview of all relevant papers integrating the topics of robotics and disassembly, this goal should be depicted by the search string itself. Hence, for this primary direction the query term "robot*" was selected, to take practically into account all relevant research on robotics itself and research limited to using robots. Because disassembly itself is both an element of research and a step in many processes, the term could be used directly as "disassembly". To connect the two fields of interest, the Boolean operator *AND* was used, which makes sure that the results of the search semantically match both terms. The time period was set to approximately 30 years, as early concepts in publications, such as Seliger et al. [28] and Dario et al. [29], still influence current researchers. The language of the research is restricted to English on the primary results of the review, as this is the lingua franca of the academic world and, therefore, the one with the highest number of useful publications. However, also a few scientific papers in German language are taken into account as they deliver valuable insights and contributions to the field of robotics in disassembly. If there was an English version of the same, this was preferred over the German one. Most German papers were added in Phase 2 from prior source records of the researchers. Those papers can be certified as additional records (see Moher et al. [22]) and were identified through other sources. The papers concerned are clearly marked as such and – if possible – linked to published research in English. The publication type is focused on peer-reviewed journal papers, as they are considered to provide the highest quality of research. Moreover, also conference papers, reports, books, and theses are taken into account, as an emerging field of research like robotics in disassembly is still relatively new instead of being part of the established discourse. A publication is excluded if it does not relate to the topic of robotics and disassembly by assessing the three stages of selection criteria presented in Sect. 3.

3 Paper Selection Methodology

The previous definition of eligibility criteria is necessary for a methodologically valid review to produce unbiased results which focus on the research topic. The inclusion criteria for the results of this review are divided into three stages as follows:

- Stage 1: Title and Abstract. In the first stage, the title and abstract as provided by Semantic Scholar was reviewed. All papers not related to the research context of this review were removed.
- Stage 2: Focus of Paper. Papers focusing mainly on robotics or robot implementations in a disassembly context were identified. Papers without a clear connection of the relevant topics or damaged and unscientific results were removed.
- Stage 3: Citation Relevance. Papers not included in the direct output of the database search but cited in the literature eligible for Stages 1 and 2 were reviewed and if relevant taken into account for the content analysis and classification. The publications were marked as additional records.

Following this procedure, 5089 papers were selected directly from the Semantic Scholar search results and 35 papers were added as additional records, leading to an overall result of 5007 papers with all duplicates removed. Duplicates were screened by title with different orthographies taken into account. If years or venues of duplicates differed, either peer reviewed journal publications were preferred over conference presentations or the more recent publication was considered revised and was therefore kept. As depicted in Fig. 4, the first refinement stage excluded 4778 results from the title and abstract. Many of these

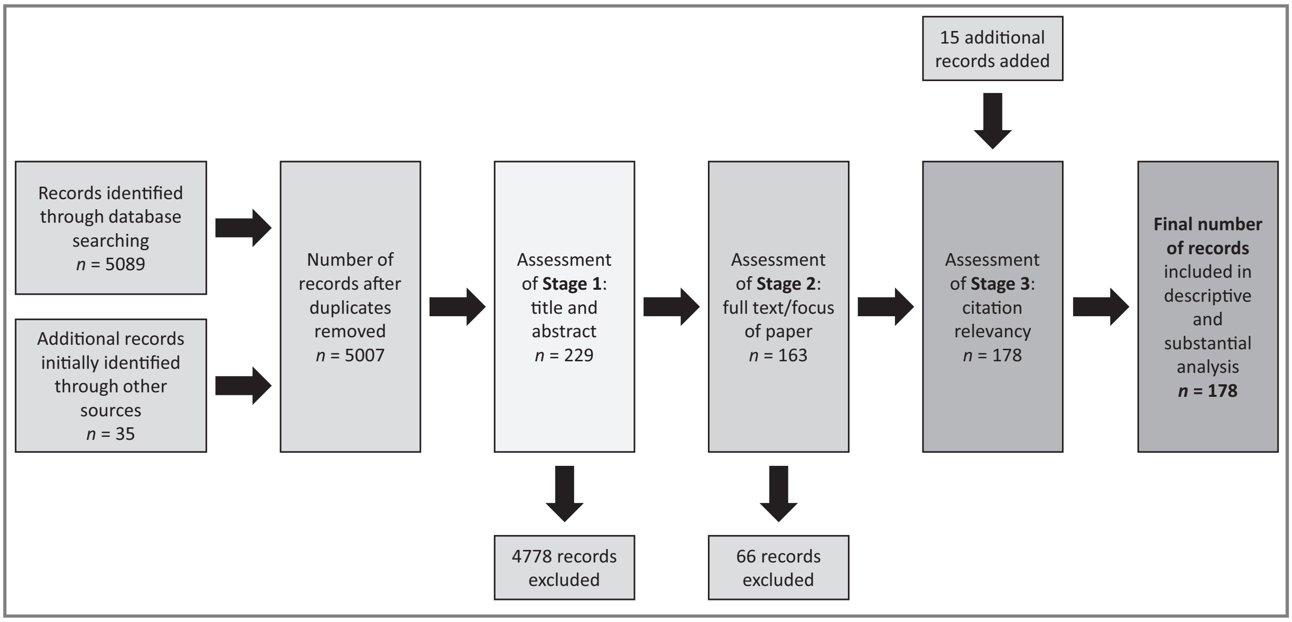

Figure 4. Paper selection methodology.

papers were either from a generally unconnected field, like medicine and biology, or just focusing on one research field not taking the other into account, e.g., pure robotics research. In advance of Stage 2 assessment, 11 results were removed because they were damaged, incomplete, or could not be found as an English publication. The Stage 2 process involved a close reading of the result's contents, leading to the exclusion of 66 papers due to a lack of relevance for the topic of robotics in disassembly or due to a misinterpretation of title and abstract, such as self-configuring robot related papers (e.g., [30]). Also, a few more general papers on disassembly line balancing were dismissed (e.g., [31]), even though a high number on path planning and sequence planning were considered relevant for practical robot applications in this field. Furthermore, the Stage 3 methodology was included in the review process to establish a holistic loop and minimize the chance to miss relevant research clusters and papers due to filter bubbles. The citation relevance review resulted in only 15 additional records identified due to citation in second stage records without being part of the control group, while all but two of those papers were at least ten years old. All added records of Stage 3 were marked as such in the final results.

In total, 178 records were found as final results of the collection (Phase 2) and screening process (Phase 3) of this literature review. In the following sections, these records will be analyzed in a general, descriptive analysis and in a content analysis leading to a classification scheme.

4 Descriptive Analysis of Sources

The descriptive analysis of the identified records aims to evaluate the 178 selected papers on general criteria to draw a map of the current research landscape on the topic of robotics in disassembly. Therefore, the following perspectives are assessed: papers across years, papers across venues/form of publication, and papers by geographical distribution regarding the first/corresponding author.

The time horizon of this review was set to approximately 30 years, from March 2019 back to 1989. The beginning of robotics in disassembly as an emerging trend can be set to the mid-1990s with a first over-proportional rise in the year 1996. Despite the fact that the amount of publications fell slightly in the following years, a level of five to eight publications on average was established from 2004 onwards. A peak of 13 publications in 2015 and a constantly high level until 2018 shows that this field of research is gaining new momentum, which is a coherent observation to the entire range of topics related to circular economy [9]. In addition to the general increase of publication frequency in CE topics, also new research groups have emerged, e.g., in Romania (eleven publications since 2011) and Australia (seven publications since 2012). Looking at the types of publications, conference papers (51.7 %) and journal publications (38.8 %) are clearly leading. As an emerging research field, the dominance of conference papers stresses the novelty of the proposed results, especially regarding applied demonstrators of robotic disassembly cells. The first monograph on the topic of disassembly automation was published in 2015 [20], and its contents strongly relate to the journal and conference papers of the authors from the related workgroup [32–35]. Published theses, scientific reports, and book chapters only make up a minority in the canon of relevant literature.

Regarding the geographical distribution of research publications on robotics in disassembly, Fig. 5 shows that Germany, the USA, and Spain are leading in the total number of publications. Taking the publication years into account, Germany and the USA hold their current position because of their constant publication output since the beginning of this research field in the 1990s. Romania has the highest output considering the time they have been present in this research field, even though the publications are mostly conference papers, all from a single group of connected researchers. Moreover, 13 out of 15 papers from Germany after 2010 were conference publications, which is different to the other leading countries in this research field who have more journal publications in relation to their conference papers, e.g., USA, having a ratio of 13 to 10. On a regional assessment, Europe dominates the disassembly automation research. A reason for this may lie in the strategy proposed by the European Union to expand CE approaches in 2015, which was widely adapted and promoted by national initiatives [36].

5 Content Analysis and Classification

The papers included in the review can be divided into several categories on a top-level evaluation. As displayed in Fig. 6a, the first difference regarding the automation of disassembly is the amount of information available to plan and potentially execute the process. The automation processes where the parts and sequences are known in advance dominate most of the early publications from Ba et al. to Tonko et al. [29, 37–41]. Also, in this group of papers, 63 % of the publications apply scientific methods and techniques to case studies and real robotic examples, such as Chen et al. [42] and Li et al. [43]. Furthermore, half of the records in this study work on the basis of known parts only, therefore concerning sequence- and path-planning methods. In total, 64 papers directly target the topic of sequence planning, albeit only nine of them leave the area of basic research, including practical examples of robotic implementation, e.g., ElSayed et al. [44] and Friedrich et al. [45]. Moreover, 14 papers (8 %) involve an automation approach without necessary a priori knowledge. These papers deal with learning models for robotic controllers [46] or agent-based configurations, mostly equipped with cameras and sensors to identify fasteners and components autonomously [47–53] and more abstract concepts of potentially autonomous systems and approaches [54–58].

In Fig. 6b, the difference between predefined processes and flexible automation of disassembly processes (flexible automation meaning in this context: knowledge about parts, no rigid sequences or paths, suitable for high numbers of variants) is shown directly. More than half of the papers (98 papers) concern flexible processes including sequence planning and 44 % (79 papers) deal with predefined processes. One paper, by Främling et al. [59], could not be put into those categories as the topic focuses on IoT communication methods while also affecting recycling and disassembly, which could be applied in both previously named groups in this review.

The consideration of actual robotic examples is evaluated in Fig. 6c. Most papers include robotic examples (94 papers), either in the form of concept studies or in the form of demonstrators and prototypes. Papers without examples (84 papers) mainly focus on sequence planning, path planning, and new control approaches. Out of the 94 papers which contain robot examples, 64 were linked to applied research and 30 could be marked as rather fundamental and more theoretical in this context.

The differentiation between applied research and basic/fundamental research was made according to Bentley et al. [60]. Applied research is more practically oriented, whereas basic research is theoretical, expanding the existing base of knowledge. In many works, those two categories blend into one another. For this review, a research paper was considered as basic research if a new approach is presented theoretically as a concept, while applied research seeks to evaluate or demonstrate a concept with actual hardware and parts under

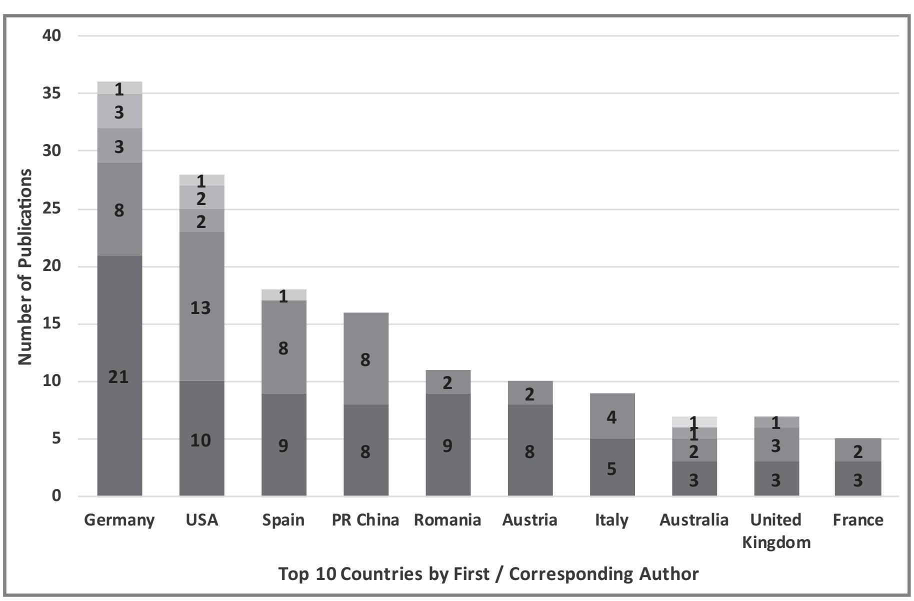

Figure 5. Geographical distribution of papers and form of publication for the Top 10 countries.

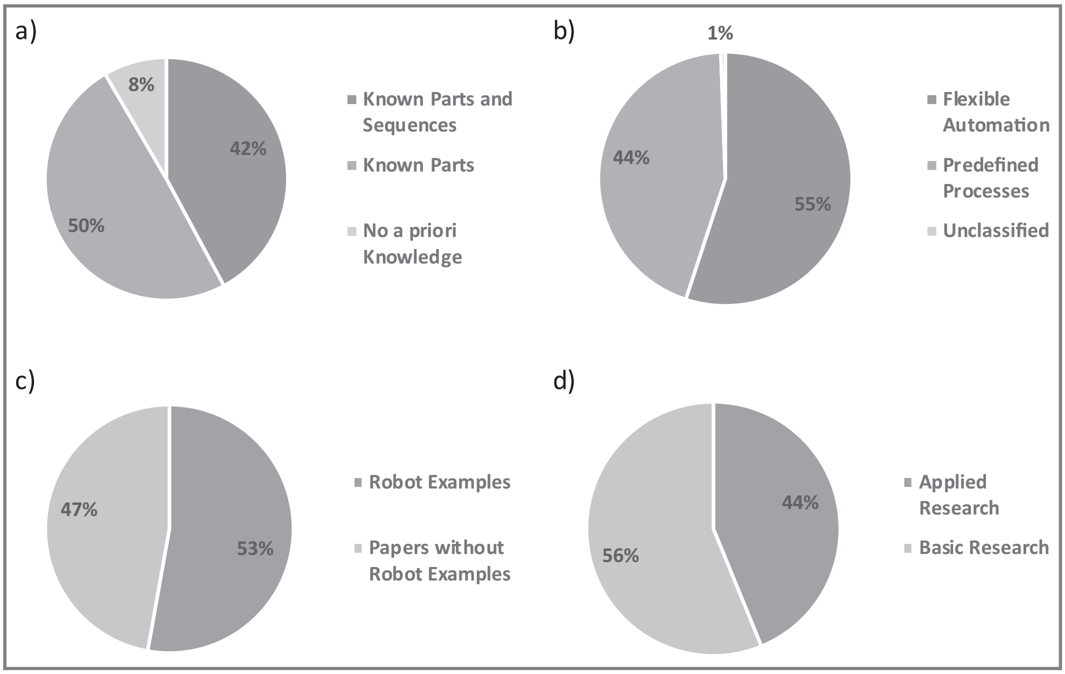

Figure 6. General categories of the reviewed papers.

practical conditions. As Fig. 6d shows, 100 out of 178 papers (56 %) are regarded as basic research on the topic of robotic automation in disassembly. The authors acknowledge that in individual cases, this differentiation does not cope with the research evaluated, as applied research could of cause also expand the existing base of knowledge and requires concept development. The analysis of individual papers rather than the analysis of the development of research groups and specific projects in the scope of this investigation further limits the absolute selectivity.

To establish a framework of research on robotic disassembly automation as proposed in the initial questions of this paper, the four most relevant dimensions are identified from this categorization. On one axis, "applied" and "basic" research and on another axis "predefined processes" and "flexible automation" will therefore be used for the classification and display of the reviewed literature in the following subchapters. In addition, the contents of the papers are analyzed and clustered for their main topics.

5.1 Analysis of Contents

For the detailed analysis of contents, the authors extracted the main topics from each paper and clustered them for the most common keywords identified. The list of the ten most relevant keywords is displayed in Tab. 3. Every publication could be assigned to more than one keyword.

Sequence planning is the largest topic covered in the research framework of robotics in disassembly. Most cases with known parts and flexible operations focus on the mathematical generation of an optimal sequence due to predefined factors and metrics. Early adopters, such as Strege et al. [61], introduced a process planning of the disassembly cell by using Petri nets, which is still an effective tool for managing adaptive planning situations, see Minca [62] and others [63–67]. Due to the high level of uncertainty concerning the parts and the process (inhibitors, see Sect. 1.2), information model approaches [68–70], and decision processes regarding the optimization of process cost or multiple objectives are present in the latest publications, e.g., Feng et al. [71] and others [1, 72–76]. Additionally, changing the sequence due to path planning problems, such as feasibility, obstacles, or geometric features, is also covered in sequence planning papers [77–82]. The researchers

Table 3. Most relevant keywords for content analysis.

Keyword	Number of matching publications
Sequence planning	65
Robotic application	41
Vision systems	33
Path planning	32
Decision making	21
WEEE	19
Human robot collaboration (HRC)	16
Agent-based systems	12
Specific tooling concepts	12
Electric vehicle components	9

employ many algorithmic approaches for an optimized sequence planning. Apart from Petri nets and fuzzy logic [65, 66, 83–86], Kongar et al. [87] and other authors use genetic algorithms [86–93], artificial ant colonies [57, 94, 95], and artificial bee colonies[85, 96], backtracking algorithms [72] and general (profit) optimization algorithms [58, 97–102]. Another trend in the topic of sequence planning is selective disassembly of concrete parts, be it for product quality or process cost [58, 103–107].

The second most common keyword in content analysis is robot application. Most of the 41 classified publications show real life applications of robotized disassembly, especially in the automotive [41, 108–118] or electronics (WEEE) domain [15, 33, 44, 49, 119–132]. Concerning the disassembly of cars, two different approaches can be described: the disassembly of a module from the car itself or the disassembly of certain car parts and subassemblies. The former is mostly concerned with handling tasks and path planning processes, e.g., Büker et al. [108] or Sánchez et al. [110], whereas the latter employs more specialized ways of actual disengagement by the application of tools and vision technologies (Bdiwi et al. [114]).

A new research trend observed in recent years (from 2012–2019) is the disassembly of electric vehicle components [43, 109, 111, 112, 116, 133–136]. Apart from the robot applications, WEEE is also targeted on a theoretical level. Concept papers by Jin et al. [137] or a process benchmark in respect of the overall cost by Yuksel et al. [138] and a paper on mathematical process modeling by Lee et al. [79] complement the papers with application examples or sensing technology also listed in this section [15, 44, 120–126, 129, 130, 139–142]. Moreover, mobile robot applications in a manufacturing system with the possibility for disassembling defective parts directly are presented in the research of Minca et al. [62, 143–146] and others [147–151], all part of the same lab in Romania. Apart from 6-axis robots, also Scara robots [123, 152] and Cartesian robots [153] are used in some concepts. Kasperzyk et al. [154] introduced an application in the building sector as a robot assistant for the automated rebuilding of disassembled modules. Duflou et al. [155] present an overview of multiple application cases, focusing on the feasibility of disassembly in general. Their conclusion, that a specific product design is mandatory for an effective disassembly, makes it an important key paper for design-based approaches, affirming Reap et al. [156], who proposed a value-oriented idea of design for disassembly guidelines and Takeuchi et al. [157], who suggest embedding the disassembly sequence into product design.

Furthermore, advanced sensing technologies in robotic applications such as vision systems or combined sensor systems and specific tooling concepts are of great importance to the successful automation of disassembly processes. Vision systems are either used for identification of components only or also for targeting parts in robotic trajectory planning. The early works of Ba et al. [37] as well as Dario et al. and others [29, 38, 39, 119, 152] use vision technologies, partly in combination with tactile sensors, to achieve the required accuracy. Delimiting the early concepts, Tonko et al. [41, 158] summarized a lack of computation power as a main issue for the non-applicability in an industrial environment. As a part of the basic research, Umeda et al. [159] proposed a concept with a shape recognition algorithm specifically on the context of assembly and disassembly. Moreover, the identification of fasteners was firstly evaluated by Gengenbach et al. [160], followed by Pomares et al. [161, 162], Gil et al. [140], Bdiwi et al. [114], and Vongbunyong et al., e.g., [20]. Besides feature recognition approaches, Ata et al. [163] propose a concept of color sensors for automated sorting in disassembly automation contexts, which has not since reappeared in other research papers on the reviewed topic. Furthermore, an approach to detect partial occlusions is presented by Gil et al. [164] in order to allow a reliable visual region segmentation of assemblies. Understanding the structure of an assembly to autonomously disassemble it is researched by Wang et al. [165] by algorithmic detection of subassemblies.

Specific tooling concepts were sometimes combined with sensorial features such as the concepts depicted by Hohm et al. [166], Schumacher et al. [167], and Mironov et al. [168] show. In-hand manipulation and high versatility are features of the KIT Swiss Knife Gripper presented by Borras et al. [169] and a flexible gripper by Schmitt et al. [170], whereas Feldmann et al. [171] and Nave et al. [172] state that (semi-)destructive disassembly is mostly a better way to efficiently install processes rather than complex and time-consuming operations with specialized tools.

After the identification and detection of the required part, the robotic disassembly cell needs successful path planning to be able to accomplish its task. Zussman et al. [173] propose a model of adaptive path planning based on Petri nets to compensate general process uncertainties. The avoidance of any collision between the acting robot and the disassembly environment is discussed in Ferre et al. [174], followed up by Zhang et al. [175], Peng et al. [176, 177], Guo et al. [178], and Schneider et al. [179], also covered in Thomas et al. [180] regarding narrow passage problems. Taking the CAD model into account, Iacob et al. [181] determine possible paths based on contacting surfaces and component mobility. Cortes et al. [182] alter configuration parameters of the path planning algorithm to improve the performance while considering articulated parts and their movability, comparable to a modular approach by Tani et al. [183]. In addition, Zebedin [184] considers a process FMEA as a useful tool for planning robotized disassembly.

In certain situations, apart from the trajectory itself, grasping points have a tremendous effect on the disassemblability. Puente et al. [185] performed their research in this area on a key/lock problem. Additionally, path planning for specifically targeted parts is examined by Aguinaga et al. [186], based on research connected to maintenance tasks in the aerospace sector [187, 188]. This case of selective disassembly leads directly to the research on decision-making in the context of disassembly automation. A learning controller based on Markov decision algorithm was firstly presented by Liu et al. [46], later supplemented by reinforcement learning research of Reveliotis et al. [189] and decision tree models of Torres et al. [105] as well as many of the sequence planning papers named above, e.g., [86, 94, 103].

Optimization of cost and quality are in the focus of the papers of Zussman et al. [190] and others [71, 85, 96]. On which basis the decision is being made is a topic in Apley et al. [191], where a way of evaluating the condition of screw connections by disassembly is presented. Besides decision making on parts, decision making on process components, such as multiple robots and their task distribution is dealt with in Torres et al. [192]. Smith et al. [193] propose a way of modular product design for parallel removal of selected parts in disassembly operations and show how design for disassembly could affect decisions made in selective disassembly. Expanding the idea of decision making in disassembly planning, Pavliska et al. [194] describe a concept of a multi-agent system for robotized disassembly with a specific decision-making unit. An early and rather vague concept of autonomous disassembly was also presented by Tani et al. [195]. These agent-based systems follow the principle of distributed system parts (agents) complementing each other to a system fulfilling the requirements for the required task. Kopacek et al. [130, 196] depict the concept of an agent-based system for hybrid disassembly in WEEE sector, following the principle of using the robots only for handling and simple operations while they still rely on human workforce for more complex tasks. Moreover, the idea of knowledge-driven mobile robots relying on an individual information database in an agent-based system is proposed by Koppensteiner et al. [47, 197], albeit no industrial robots are used here, but specific mobile robots for the disassembly of Lego parts. The works of Vongbunyong et al. [20, 32, 34] are, on the other hand, based in the industrial environment of LCD-monitor dismantling. Their concept of an agent-based system using cognitive robotics (reasoning, execution monitoring, and learning) with agents on three different control levels can be regarded as a milestone in the development towards an autonomous robotic disassembly system.

Van Moergestel et al. [198] outline a concept of a manufacturing system with a special product agent, which collects relevant process information during assembly for guidance of the disassembly operation at EOL. This information contains an optimal sequence which should enable a robotic system to disassemble the product without necessary a priori information. On top of that, Jungbluth et al. [199–201] further optimize and improve the concept of Vonbunyong et al. [33] by focusing strongly on the requirements of human robot collaboration in combination with a performant, nearly autonomous system. The trend research topic of HRC is incorporated in many projects of disassembly automation, following a hybrid approach to specific task distribution. Firstly described in Kopacek et al. [196], semi-automatized disassembly as a cooperation between human workers and robots is targeted in the workgroup of Díaz et al. [202], in which a concept for a direct cooperation system in a single disassembly cell is shown. Cruz-Ramírez et al. [203] only use the robot for auxiliary tasks in dismantling operations in the building sector, which as a principle could also be applied in an industrial environment. Tracking the human operator with vision technologies for a safe HRC in disassembly is presented by Corrales et al. [204] as a concept and validated experimentally by the disassembly of refrigerators. Wegener et al. [111, 134] also use visual surveillance of the robot cell to make safe collaboration possible. Tellaeche et al. [205] describe further use cases of HRC in industry, also a disassembly case in which a human and a dual arm robot disassemble complex objects. Furthermore, learning by sensual perception [49] or demonstration [50] could be achieved by a combination of HRC and vision technologies. The latest work, at the time of this review, with a combination of HRC and disassembly is from Cesta et al. [206], describing a conceptual control architecture for AI enforced HRC task planning in assembly and disassembly situations.

In summary, it can be said that the current trends and developments in robotic disassembly are aimed towards highly autonomous, collaborative systems. The use of sensors, especially vision technologies, is widely established and the application of AI algorithms for an optimized sequence and path planning is no longer limited by the computation power required. However, the amount of research is still small in comparison to robotic assembly and other industrial sectors. Only a few groups of scientists so far have developed full-scale concepts which could be proven by successful application. Research gaps are clearly visible when it comes to an efficient information management on all levels of the control infrastructure regarding relevant product and process information. Integrating these potentials to an advanced system concept using IoT technology and an integrative digitalization framework to make robotic disassembly a practical and economically feasible use case will be a central part of the future research of the project Recycling 4.0.

5.2 Classification Framework of Reviewed Literature

The visualization of the framework on robotics in disassembly is based on the four categories defined in the beginning of Sect. 5. A relevant differentiation can be made between applied research (demonstration of a concept or principle) and basic research (presentation of a new concept or mostly theoretical work). These two dimensions mark the abscissa, whereas the ordinate functions as a timeline. Following the trend towards autonomous disassembly, the second distinction is made between predefined processes and flexible automation of disassembly processes. Figs. 7 and 8 display

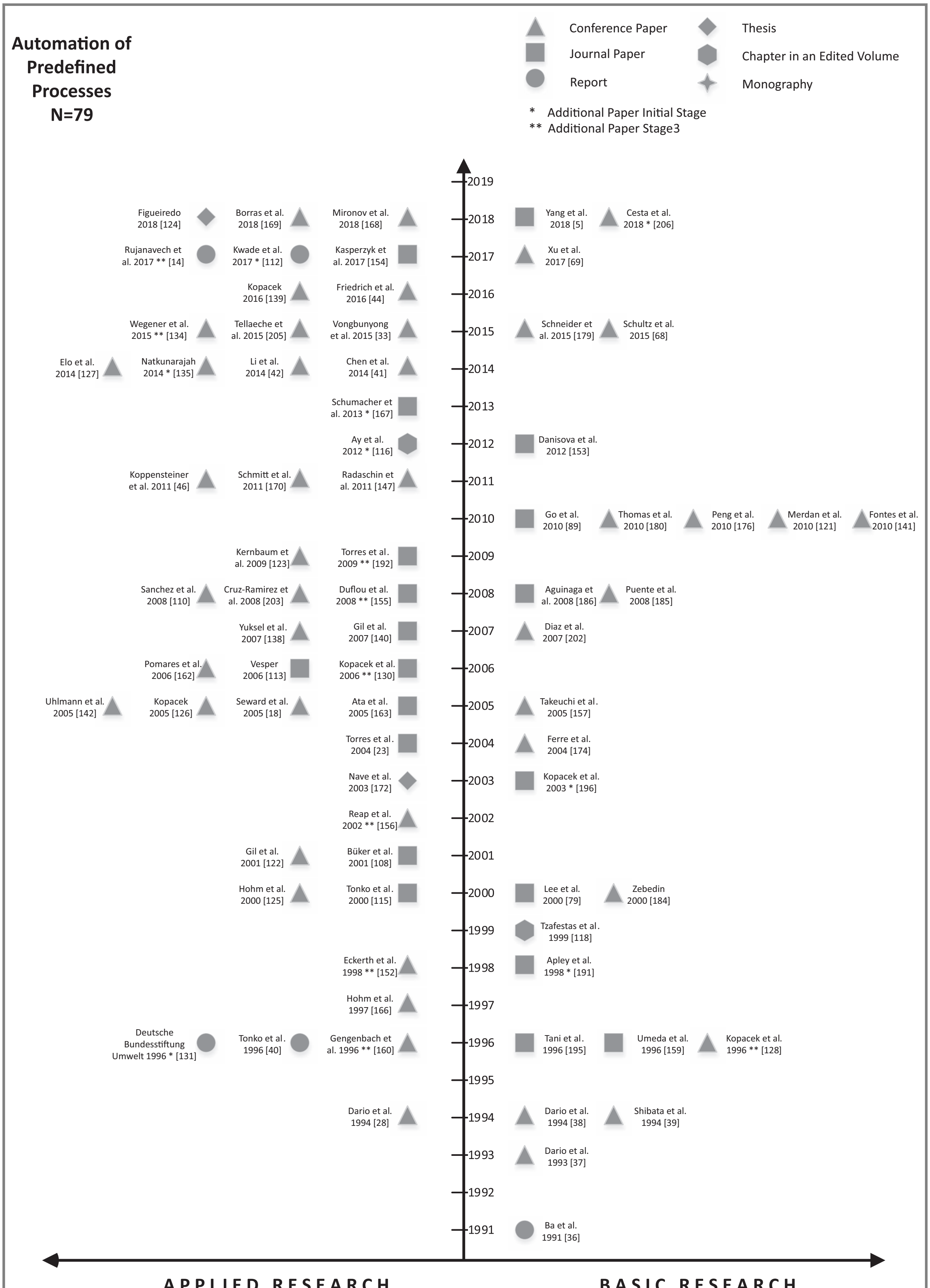

Figure 7. Classification of papers regarding predefined disassembly processes.

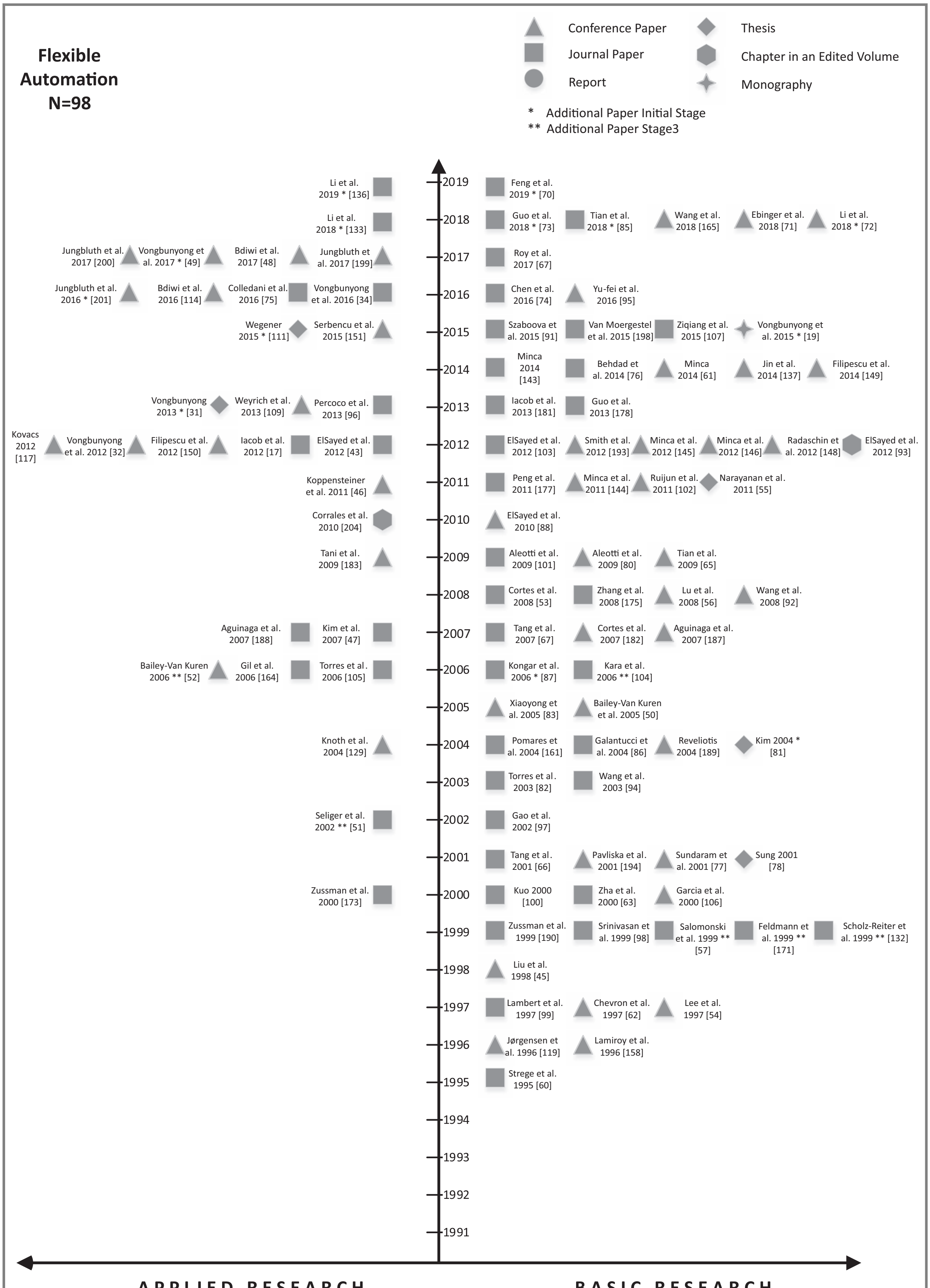

Figure 8. Classification of papers regarding flexible disassembly processes.

the frameworks worked out. For each paper, the type of publication is also given. Additional records from the pre-assessment and from stage one are clearly marked as such.

6 Conclusions

A more efficient and more widely applied CE process is a fundamental requirement of the sustainable development goals set up to tackle climate change and the problems of overpopulation in consumerist societies. Using robots in disassembly tasks could bring tremendous benefits if the current inhibitors can be overcome. This paper proposes a holistic analysis of the current research in robotic disassembly. The basis of this research is an SLR of 178 papers. The dominating research trends derived from this empirical review show a strong development towards completely autonomous robot cells for disassembly and an improvement of HRC conditions and processes in the disassembly domain. Furthermore, the algorithmic optimization of sequence planning, e.g., by employing AI strategies will also benefit the feasibility of automatic robotic disassembly. The method utilized also depicts future potential for research regarding the integration of disassembly processes into a superordinate CE information system to use the plethora of information gained and required in this very step of the value chain. Another implication for stakeholders outside academia would be to work more intensively on the related topics, as future legal regulations might require higher rates of certain products to be recycled than is the case today.

Seeing disassembly as a potential to regain valuable materials at a higher quality or to potentially reuse or remanufacture specific modules and parts makes it also more attractive to consider investing in this field. A huge step in the disassembly and dismantling sector at this time would already be the implementation of hybrid disassembly processes working in HRC robot cells. These forms of robotic disassembly demand less effort concerning investments in line technology and engineering and are easier to adapt, if needed. Currently, Germany and the United States play a leading role in this research area, closely followed by Spain and China. Most topics, as identified in Sect. 5, can be related to certain countries or groups of researchers at present, as the field of robotic disassembly has not yet arrived in robotics mainstream research. An important conclusion is that disassembly is not necessarily reverse assembly. Sometimes specific joining technology or geometrical features prevent a reverse process, making it more difficult to implement processes for robotic disassembly if the purpose was not already considered in the design phase. The sorting of the reviewed papers after the relevant difference of predefined and flexible processes will help future researchers to find the relevant key publications for their subtopic in the field of robotic disassembly more easily, while providing a set of adjacent papers on similar contents (see Sect. 5.1) as well.

Regarding the platform used, Semantic Scholar delivers output from a wide range of sources available in online databases. The engine extracts meaningful structures besides the text, such as figures and tables, while taking links to other papers into account, giving highly precise results for the topics searched for, even though still in development. However, the metadata for a few publications was incorrect and some duplicates occurred, which both needed to be rectified by the authors. The search engine was not evaluated for the risk of bias in this study. The architecture and a complete description of its function as well as open API are available for maximum transparency.

A clear limitation of this research is the applicability of general robotics knowledge in the field of disassembly which was not considered due to the specific search string and aim of this paper to limit its scope to robotics and disassembly in contextual publications. There may be many papers presenting technologies or concepts that might benefit disassembly processes not present in this publication due to this limitation. However, the effort to evaluate this applicability in a vast number of general robotics publications is not really feasible as it would certainly exceed the resources of most research projects.

The authors hope to encourage further research in this field by presenting this review paper. Future studies on the information processes and system concepts towards an autonomous disassembly system will be investigated as a part of the Recyling 4.0 project and other ongoing projects at their institutions.

Supporting Information

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